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WADC TECHNICAL REPORT 52-183

ANNUAL REPORT ON RESEARCH FOR USE IN ANC-17 BULLETIN, "PLASTICS FOR AIRCRAFT"

DONALD G. COLEMAN
U. S. DEPARTMENT OF AGRICULTURE

DECEMBER 1952

WRIGHT AIR DEVELOPMENT CENTER

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ANNUAL REPORT ON RESEARCH FOR USE IN ANC-17 BULLETIN, "PLASTICS FOR AIRCRAFT"

Donald G. Coleman
U. S. Department of Agriculture

December 1952

Materials Laboratory
Contract No. AF 18(600)-70
RDO No. 614-12

Wright Air Development Center
Air Research and Development Command
United States Air Force
Wright-Patterson Air Force Base, Ohio

FOREWORD

This report was prepared by the Forest Products Laboratory, Forest Service, U. S. Department of Agriculture, on Contract No. AF 18(600)-70. The contract was initiated under Research and Development Order No. 614-12, "Structural Plastics", and was administered under the direction of the Materials Laboratory, Directorate of Research, Wright Air Development Center, with Mr. D. A. Shinn acting as project engineer.

ABSTRACT

Developments in the program of research in plastics for aircraft conducted by the U. S. Forest Products Laboratory are summarized. The approach has been in general to derive design criteria mathematically and then to check by test. Thirteen technical reports issued during the several years this project has been under way are abstracted.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDING GENERAL:

M. E. SORTE
Colonel, USAF
Chief, Materials Laboratory
Directorate of Research

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INTRODUCTION

This annual report by the U. S. Forest Products Laboratory covers developments in the program of research in plastics for aircraft conducted by the Laboratory during the fiscal year 1952. Actually, however, since it is the first such report prepared during several years of research, effort has been made to summarize work on all projects included in the current program, some of which were concluded before the 1952 fiscal year began. This report, therefore, is intended to serve as a convenient reference for the status of the entire current research program. It is planned that future annual reports will cover only those projects and items on which work was done during a given fiscal year.

Item 1. --Mechanical Properties of Parallel-laminated Laminates

This project is designed to furnish data on the strength properties of parallel-laminated laminates in the wet and dry condition. Twenty-one different laminates are involved, of which the majority are glass fabrics laminated with polyester resin. The other laminates are glass mat with polyester resin (one), glass fabric with phenolic resin (two), and cotton cloth with phenolic resin (one).

Report No. 1820 (February 1951) presents the results of tension, compression, bending and shear tests of 14 laminated plastic materials. Tests of laminates were made after the specimens had been subjected to normal or to wet conditioning. The mechanical properties of the laminates, both dry and wet, are presented in the form of tables and by average stress-strain curves. The results of the glass-fabric-polyester laminates are considered to be typical of laminates made with any polyester resin conforming to U. S. Air Force Specification 12049 and a specific glass fabric with finish 114. The mechanical properties of such laminates are substantially reduced after exposure to wet atmospheric conditions.

Tests of the remaining laminates are going forward.

Item 2.--Mechanical Properties of Laminates Not Parallel-laminated

Various fabrics, and thus the parallel laminates made from them, have different properties. The properties of some parallel laminates also depend upon the direction of application of the stress with respect to the warp direction of the fabric. Laminates having nearly any desired combination of properties may therefore be formed by combining fabrics or by cross laminating. The number of possible combinations is so large that empirical determination of properties is impractical.

This project was designed to develop procedures for predicting the strength properties of cross-laminated or composite laminates from the properties of parallel laminates of the component fabrics, and to test the validity of these procedures by comparison of predicted strength properties for a number of laminates with strength properties found by test. Three types of laminates were tested: (1) Cross laminates of each of three different fabrics; (2) a parallel laminate consisting of alternating layers of different fabrics; and (3) parallel laminates consisting of a core of one fabric with facings of varying thicknesses of another fabric.

Report No. 1821 (February 1951) shows that the properties of glass-fabric laminates may be varied by varying the orientation of the laminations or by combining laminations of differing properties. Reported are the results of tests of cross laminates of three fabrics varying in strength parallel and perpendicular to their warp. Also tested was a parallel laminate combining two of these fabrics in alternate laminations. Methods are given for predicting the properties of the laminates tested, based on properties of parallel laminates.

Work on the third type of laminate is under way.

Item 3.--Mechanical Properties of Two Laminates at Angles to the Orthotropic Axes

It has been suggested that glass-fabric laminates might be treated as an orthotropic material, and that the general elastic equations and interaction formula applicable to plywood might similarly be used for this material. Report No. 1803 (April 1949) presents a study of the elastic and strength properties of a glass-fabric laminate made of 181-114 fabric, a satin-weave fabric of about equal strength in the warp and fill directions. Tests were made at various angles to the grain, on specimens so proportioned as to preclude buckling or failure because of elastic instability. Comparisons between the experimental and theoretical values in tension, compression, and shear are presented. Also included in the report are data showing the effect of grain direction upon the bearing, edgewise-shear, and interlaminar-shear properties of the material.

Supplement 1803-A (April 1950) presents the results of tension, compression, and shear tests of two other glass-fabric-base plastic laminates similarly tested. The 112-114 laminate discussed in this supplement is made of a plain-weave fabric having a warp-to-fill strength ratio of about 3 to 2, and the 143-114 laminate is made of a unidirectional-weave fabric having a warp-to-fill strength ratio of about 11 to 1. Thus, these laminates represent three glass fabrics having entirely different properties. Except for the panel-shear test values, there was good correlation between the experimental and theoretical values. The difficulty of making an accurate shear test is recognized, and it may be that the computed shear values are more nearly correct than those measured by the shear tests.

Item 4. --Mechanical Properties of a Laminate Designed to be Isotropic

While the usual glass-fabric-reinforced laminates are orthotropic in character, the individual plies can be arranged in such a way as to produce a laminate which is essentially isotropic. Mathematical analysis of a method for construction of an isotropic laminate has been completed.

Item 5. --Bearing Strength of Three Laminates Under Tension Loading

Report No. 1824 (June 1951) presents the results of about 400 bolt-bearing tests of three glass-fabric-base plastic laminates made with a polyester resin conforming to U. S. Air Force Specification 12049. The laminates were either 1/4 or 1/8 inch thick and were tested at angles of 0°, 90°, and 45° to the warp direction, at D/t ratios of 1 and 4, and in both the dry and the wet conditions. Included are data on the bolt-bearing properties of the materials and on the effect of end or edge distances. The laminates were reinforced with glass fabrics of widely different properties, so that some difference in bearing properties might be expected. The end and edge distances required to preclude failure to the end or edge of the specimen were substantially different for the three laminates. However, an end distance of 4D and edge distance of 2-1/2D were large enough to prevent such failures, regardless of the fabric used.

With adequate end edge distances, the stresses at proportional limit and at maximum load were (1) highest at the low D/t ratio, (2) highest when laminates were tested in the dry condition, and (3) about the same at 45° as at 0° or 90°

Items 6 and 7. --Tension Strength of Lap Joints and Scarf Joints of Two Laminates

Scarf joints and lap joints in two glass-fabric-base plastic laminates were tested in tension and in compression. In each case the joints were made between sections of the cured laminate. The scarf-joint tests involved a variety of gluing techniques and adhesives as well as a range of scarf slopes. The lap joints were made with several gluing techniques and in lengths up to 3-1/2 inches.

As reported in Report No. 1818 (October 1950) the scarf-joint tests indicated that the efficiencies that could be attained depended on the adhesive used and the technique of using it, as well as on scarf slope. For a given slope, efficiencies appear to be higher in compression than in tension. Efficiencies in tension ranging up to 70 to 80 percent at a scarf slope of 1 in 28 were obtained with one adhesive when tested in the dry condition. After exposure to high humidity, efficiencies were about 10 percent lower than for joints tested in the dry condition. Choice of a different adhesive permitted attainment of efficiencies as high as 90 percent in the dry condition and 80 percent in the wet condition at a slope of 1 in 20.

Lap joints are inefficient in transmitting tensile stress. Even with lap lengths of 3-1/2 inches, only about one-fourth to one-third of the tensile strength of the laminate could be developed. In compression, however, efficiencies of 60 to 80 percent were found at this lap length. At the 3-1/2-inch length, the majority of the specimens did not fail in the joint when tested in compression.

Item 8. --Effect of Defects in Laminates on Tensile and Compressive Strength of a Typical Laminate

Report No. 1814 (June 1950) presents results of 52 tension and 52 compression tests made to determine the effect of defects on the mechanical properties of a glass-fabric-base plastic laminate. Because even carefully controlled fabricating procedures result in occasional defects, some indication of the effect of these defects on the strength of the laminate is desirable.

Seven laminated panels were fabricated for these tests: one control panel, one with high resin content, two with low resin content, one with surface wrinkles, one with butt joints, and one with lap joints.

An increase in resin content resulted in lower values of modulus of elasticity, proportional limit, and ultimate stress in tension, and a lower modulus of [illegible] The ultimate stress in compression, however, increased with increased resin content within the range of resin content tested. Surface wrinkles lower the strength in tension and compression, and the deeper the wrinkle the greater is the reduction. Butt joints lower the tensile strength of the laminate but the compressive strength (within limits) is not appreciably affected. If a single butt joint occurred in a six-ply laminate, the tensile strength at the joint would be about five-sixths of the tensile strength where the plies were continuous. Lap joints, in general, would be expected to lower the tensile strength of the laminate, and the reduction would depend upon the efficiency of the particular joint. An increase in length of lap would be expected to raise the efficiency. The compressive strength (within limits) does not appear to be appreciably affected.

Item 9.--Effect of Prestressing in Tension or Compression on the Mechanical Properties of Two Laminates

Report No. 1811 (September 1950) presents the results of 36 tension and 45 compression tests made on two glass-fabric-base plastic laminates. The laminated specimens were prestressed to various percentages of the ultimate stress, and a study was made of the effect of this prestressing on the mechanical properties and set. All tests were made after normal conditioning of the specimens.

The tests showed that with 181-114 laminate, resin 2, which might be considered a typical glass-fabric-base plastic laminate, the stress-strain curve of the material after it had been prestressed in tension was different from the stress-strain curve obtained on the first application of stress. Thus, for laminates of this type, the results indicate that the values of modulus of elasticity and of proportional limit, as calculated from the usual tensile stress-strain curve, may be considerably in error once the material has been stressed beyond the initial proportional limit. The 143-114 laminate, resin 2, on the other hand, showed the same type of stress-strain curve whether or not prestressed. The tensile strength of neither type appears to be affected by prestressing.

The compressive properties of the two laminates were not appreciably affected by prestressing. The greater the degree of prestressing in tension or compression, the greater was the observed set. However, the set is of small absolute magnitude.

A supplementary report, No. 1811-A (June 1951), presents the results of 18 tension tests in which each specimen was prestressed once prior to the test to failure. Four different laminates were tested, in both the wet and dry condition and the test results verify the conclusions given in Report No. 1811.

Item 18.--Effect of Span-depth Ratio Upon Mechanical Properties Obtained from Bending Tests of a Typical Laminate

A limited number of bending tests of a typical glass-fabric-base plastic laminate were made to determine the effect of span-depth ratio and thickness on the mechanical properties obtained from test. Three thicknesses of laminate, 1/16, 1/4, and 1/2 inch, were tested at span-depth ratios between 12 and 3[illegible]. A few tensile and compressive tests were included for each thickness of laminate.

The results of the tests, as given in Report No. 1807 (June 1949), show that the modulus of rupture decreases with an increase in span-depth ratio or with an increase in thickness of the laminate, and the modulus of elasticity increases slightly with an increase in span-depth ratio. For any given span-depth ratio, the modulus of rupture was markedly lower the thicker the material, even though the tensile and compressive properties, Barcol hardness, resin content, and specific gravity were closely comparable for all three thicknesses. At a span-depth ratio of 16 to 1, the moduli of rupture were about 67,000, 59,000, and 52,000 pounds per square inch for approximately 0.074, 0.27, and 0.53 inch thicknesses, respectively.

Item A.--Fatigue Properties of Glass-fabric-base Plastic Laminates Subjected to Axial Loading

Fatigue data are important to the proper design of aircraft structures. This project was designed to furnish data on the fatigue properties of three typical laminates and to evaluate the effects of such factors as high-humidity exposure, stress risers, and magnitude of mean stress. Dead-load tests were included in the project to furnish data on stress in tension versus time to failure on one material.

Report No. 1823 (May 1952) shows for the typical laminates tested, fatigue strengths at 10 million cycles on the order of one-fourth of the static tensile strength, with notches causing about 3 to 6 percent additional reduction in strength. At 10 million cycles, moisture had no affect on fatigue strength, although it did at smaller numbers of cycles. Tests at mean stresses other than zero resulted in substantially lower fatigue strength.

Results of dead load tests have not yet been incorporated into a report.

Item B. --Effect of Thickness on the Strength of Glass-fabric Plastic Laminates

Data from tests of sandwich constructions with thin plastic-laminate facings indicated that the compressive strength properties developed were considerably below those developed in tests of laminates 1/8 to 1/4 inch in thickness. This project was designed to obtain a preliminary evaluation of strength differences among laminates of various thicknesses for adaptation of test data to design. Laminates approximately 0.015, 0.030, and 0.045 inch thick were made for comparison with a laminate 1/4 inch thick. In addition to laminates made between platens, sandwich constructions with laminate facings on honeycomb and balsa cores were made to evaluate the effect of method of manufacture.

Test results, not yet available in report form, indicate strength reductions with decreasing thickness for thicknesses below about 1/16 inch. For greater thicknesses, no consistent trend is apparent. No apparent difference between facings and laminates was found.

Item C. --Effect of Exposure to Various Relative Humidities on the Flexural Properties and Weight Increase of a Polyester Glass-fabric-base Laminate

Moisture absorbed by a glass-fabric-polyester laminate exposed to temperatures of 73° F. to 100° F. and 50 to 100 percent relative humidity in controlled tests caused the flexural properties of the laminate to decrease. The relationship of strength to moisture absorption, it was found, is not a straight-line function; the rate of decrease in strength is greatest at the initial increase in moisture content. Results are covered in Report No. 1819 (October 1950).

Item D. --Effect of Different Catalysts and Different Amounts of Styrene Monomer on the Strength and Durability Properties of Glass-cloth Laminates

Static bending and Izod impact tests were made to determine how the strength and durability of glass-cloth plastic laminates were affected when the resin formulation was varied as to curing conditions, amounts of catalyst and accelerator, and amounts of styrene monomer added to the resin. Laminates made with three typical polyester resins were tested after various types of exposure. Results are given in Report No. 1825 (March 1952).

increasing the amount of catalyst or increasing or decreasing the styrene monomer content from the manufacturers' recommendations for some typical resin formulations used to make glass-cloth plastic laminates resulted in relatively small changes in static bending strength for the test conditions studied. Decreasing the catalyst content by 50 percent resulted in some loss in bending strength at standard conditions, after water immersion, after cyclic exposure, and after 1/2 hour at 160° F. Heat-curing combinations of catalyst and resin (using manufacturers' recommendations) appeared to produce better laminates than the room-temperature-curing combinations.

In most cases a reduction in bending strength resulted from exposure to the weather, elevated temperatures, immersion in water, and a cyclic exposure of alternating high and low relative humidity at 175° F. The reductions due to exposure were greater than the effects resulting from variations in catalyst and styrene monomer content. The modulus of elasticity was affected least by these exposures; the modulus of rupture was decreased considerably more; and the strength at proportional limit was reduced most.

Item E. --<u>Preparation of ANC-17 Bulletin</u>

The original ANC-17 Bulletin, issued in 1943, is very much out of date, since many of the modern structural plastics are not covered. Data from the Forest Products Laboratory, other laboratories, and the technical literature are being reviewed for possible inclusion in a revised edition of ANC-17.

FPL Report Number	Title
1803	Directional Properties of Glass-fabric-base Plastic Laminate Panels of Sizes that do not Buckle. 1949. Equations derived from the theory of elasticity are given for the evaluation of the elastic properties at angles to the natural axes of the material. An interaction equation is suggested for the evaluation of the strength properties. These equations are shown to agree reasonably well with test results.
1803-A	Supplement to Directional Properties of Glass-fabric-base Plastic Laminate Panels of Sizes that do not Buckle. 1950. Experimental and theoretical values of the directional properties of two glass-fabric-base plastic laminates are compared in tension, compression, and shear. The theoretical analysis has now been applied to three laminates having entirely different properties and, with limitations, should be applicable to other laminates reinforced with glass fabric.
1807	Effect of Span-depth Ratio and Thickness on the Mechanical Properties of a Typical Glass-fabric-base Plastic Laminate as Determined by Bending Tests. 1949. Results of tests indicate that the modulus of rupture decreases with an increase in span-depth ratio or with an increase in thickness of the bending specimens; and that the modulus of elasticity increases slightly with an increase in span-depth ratio.
1811	Effect of Prestressing in Tension or Compression on the Mechanical Properties of Two Glass-fabric-base Plastic Laminates. 1950. Results of tension tests of plastic laminates indicate that the stress-strain relationship between the first and subsequent applications of load may be different. Values of proportional limit and modulus of elasticity, based on the usual stress-strain curve, may be considerably in error for a material under service conditions

Supplement to Effect of Prestressing in Tension or Compression on the Mechanical Properties of Two Glass-fabric-base Plastic Laminates. 1951.

Previous tests of two laminates, outlined in the original report (No. 1811) indicated that stress-strain relationships may be different between the first and subsequent applications of load. A few additional tension tests of four laminates, in dry and wet conditions, verify the previous conclusions.

1814 Effect of Defects on the Tensile and Compressive Properties of a Glass-fabric-base Plastic Laminate. 1950.

Results of tension and compression tests of laminated panels having defects are presented in this report. Defects include (1) high resin content, (2) low resin content, (3) surface wrinkles, (4) butt joints, and (5) lap joints.

1818 Strength of Scarf and Lap Joints in Glass-fabric-base Plastic Laminates. 1950.

Scarf and lap joints, made between sections of cured laminate, were tested in tension and compression using various lengths of joints and a variety of gluing techniques. Tests were made after both dry and wet conditioning, and efficiencies of the various combinations are given in this report.

1819 Effect of Moisture Absorption on Flexural Properties of a Glass-fabric-polyester Laminate. 1950.

A glass-fabric laminate made with a polyester-type laminating resin was tested in flexure after exposure conditions ranging from 50 percent relative humidity to water immersion. Strength properties decreased with increasing amounts of absorbed water, the greater rate of decrease accompanying smaller absorptions; modulus of elasticity was relatively unaffected

1820 Mechanical Properties of Plastic Laminates. 1951.

Presents the results of tension, compression, bending, and shear tests of 14 laminated plastic materials. Each laminate was reinforced with a single fabric and was parallel-laminated. Tests were made after both normal and wet conditioning.

1821 Mechanical Properties of Cross-laminated and Composite Glass-fabric-base Plastic Laminates. 1951.

Reports the results of tests of cross laminates of three fabrics varying in strength parallel and perpendicular to their warp. Also tested was a parallel laminate combining two of these fabrics. Methods are given for predicting the properties of such laminates based on the properties of parallel laminates.

1823 Fatigue Tests of Glass-fabric-base Laminates Subjected to Axial Loading. 1952.

Fatigue properties of three plastic laminates, made from typical glass-fabric bases and polyester-type resin, were obtained by axial loading. S-N curves, obtained between 1 thousand and 10 million cycles, show the effect on fatigue strength of notch, cooling, warp direction, various mean stresses, or a combination of these.

1824 Bolt-bearing Properties of Glass-fabric-base Plastic Laminates. 1951.

Presents results of about 400 bolt-bearing tests of three laminates, tested under dry and wet conditions, including data on the effects of end and edge distances.

1825 Effect of Different Catalysts and Amounts of Styrene Monomer on Strength and Durability of Glass-cloth Plastic Laminates. 1952.

Test results show that the type of catalyst and amounts of styrene can be varied over an appreciable range without seriously affecting the strength or durability of laminates made with a typical polyester resin.

1816 Strength of Orthotropic Materials Subjected to Combined Stresses. 1950.

The Henky-von Mises Theory of energy is used to obtain a theory of strength of orthotropic materials subject to combined stresses. Equations are then deduced from the theory to predict the strength of orthotropic materials, (such as plastic laminates), stressed uniaxially at various angles to the natural axis of the material. These equations are shown to agree with available test values.

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